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DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Maryland 20084

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A DATA REDUCTION PROCEDURE FOR CAVITATION NOISE FROM AN OSCILLATING HYDROFOIL

by

Robert D. Pierce

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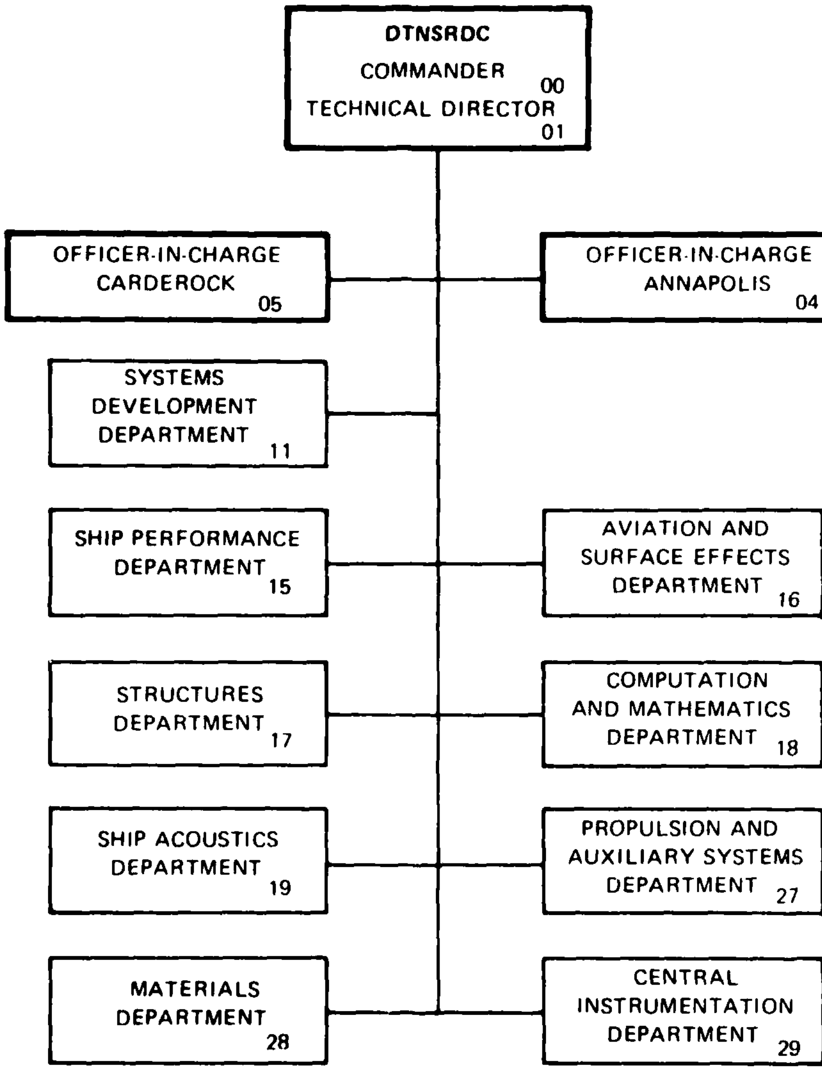

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An improved computerized technique has been used to analyze nonstationary cavitation noise from an oscillating hydrofoil. Combined analog and digital signal processing procedures were developed that use ensemble averaging techniques to quantify the average sound pressure variance as a function of the foil's angle of attack. The averages provide a quantitative basis for comparing cavitation noise produced by this hydrofoil under a finite spectrum of specific test conditions.

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LIST OF ABBREVIATIONS

a_0	Average value
a_K	Single amplitude of kth harmonic
ANSI	American National Standards Institute
ARSPV	Average Relative Sound Pressure Variance
CCP	Conditioned Camera Pulse
cm	Centimeter
cm/s	Centimeters per second
db	Decibel
DIV	Division
DTNSRDC	David W. Taylor Naval Ship Research and Development Center
DVM	Digital Voltmeter
Fm	Midband or Center Frequency
FASP	Foil Angle Synchronization Pulse
FFT	Fast Fourier Transform
ft	Feet
h	Cavitation Noise
Hz	Hertz
IRIG	Inter-Range Instrumentation Group
K	Dummy index of summation
[illegible]	Harmonic number
kHz	Kilohertz
kPa	Kilopascals
LED	Light Emitting Diode
M	Number of samples in run
m/s	Meters per second
msec	Milliseconds
n	Dummy index of summation
PCFA	Phase compensated foil angle

LIST OF ABBREVIATIONS (Cont.)

psia	Pounds per square inch
QRSPV	Quasi-Stationary Relative Sound Pressure Variance
RC	Resistor/capacitor
RSPV	Relative Sound Pressure Variance as a function of foil angle
sec	Second
T	Integration time or averaging period
T	Period of cycle
t	Time
t_n	Time at nth sample
α	Foil angle
α_s	Static foil angle component
α_a	Single amplitude foil angle component
ξ	Time into foil angle cycle
[illegible]	Phase angle of kth harmonic
τ	Dummy variable of integration

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ABSTRACT

An improved computerized technique has been used to analyze nonstationary cavitation noise from an oscillating hydrofoil. Combined analog and digital signal processing procedures were developed that use ensemble averaging techniques to quantify the average sound pressure variance as a function of the foil's angle of attack. These averages provide a quantitative basis for comparing cavitation noise produced by this hydrofoil under a finite spectrum of specific test conditions.

INTRODUCTION

Cavitation is a destructive phenomenon associated with operating propellers and hydrofoils when the local pressure on their lifting surfaces is less than the vapor pressure of the water — the water boils. Cavitation produces noise, metal erosion, loss of lift or thrust, and vibration in surrounding structures. A considerable effort is underway in the Navy to eliminate cavitation, reduce cavitation to acceptable levels, or to counter the effects of cavitation. For example, experiments are performed to study the influence of the static and time-varying pressure fields that produce cavitation. Knowledge obtained from these experiments is used to reduce cavitation through enlightened design of propellers and hydrofoils, and to predict their cavitation performance.

Experiments to investigate features of cavitation noise contribute useful information to this study. One such experiment with an oscillating hydrofoil was performed in the David W. Taylor Naval Ship Research and Development Center's (DTNSRDC) 36 inch Variable Pressure Water Tunnel*.[1] During this experiment, two types of tests were conducted: static, in which the foil was fixed at a given angle of attack; and dynamic, in which the foil's angle of attack was sinusoidally varied about an initial offset. Several runs of each type of test were

*A complete listing of references is given on page 27.

made at different water speeds and tunnel pressures. Cavitation noise data were recorded and photographs of the cavitation bubble pattern were taken.

Cavitation noise was statistically quantified for each of three conditions: (1) the sound pressure variance at the instant a photograph was taken, (2) the average variance during a run, and (3) the average variance as a function of the hydrofoil's angle of attack during dynamic runs. Procedures to obtain these sound pressure measurements for the first two conditions were relatively straightforward. But the third was not, because the cavitation noise during the dynamic runs was modulated by the foil's motion and was thus statistically nonstationary.

Typically this nonstationary data would be reduced by manually analyzing oscillograph records of the modulated noise. This experiment had almost 100 dynamic runs, and such manual analysis would have consumed a considerable man-day effort and period of time. And the results from manual analysis are observer-dependent; the eye and mind of the individual must construct the image of the "typical" noise cycle.

Accordingly, special analog and digital signal processing procedures were developed to automate the data reduction of this modulated data and to obtain observer-independent quantitative results. Especially significant was the ensemble-averaging procedure to obtain average sound pressure variance as a function of the foil's angle of attack.

This report includes a general description of the data collected during this water tunnel experiment as well as a detailed description of the procedures used to quantify the data. The first section, Test Data, provides an account of how the experimental data were acquired. Also, in this section, the main characteristics of the hydrophone signal (cavitation noise plus contamination noise) are related to the signal processing procedures necessary to quantify this data. The second section, Data Reduction, gives a detailed description of the signal processing procedures used to statistically quantify the experimental data. First, a general description of these procedures is presented; then the procedures are detailed in two parts: Analog Signal Processing and Digital Signal Processing. The last section, Conclusions, summarizes the quality of the procedures and presents recommendations. The appendix presents a sample output from the computer processing.

TEST DATA

DATA ACQUISITION

The experiment took place in DTNSRDC's 36 inch Variable Pressure Water Tunnel. A hydrofoil section placed in the flow was subjected to various water speeds and tunnel pressures, both with the foil at a fixed angle of attack and with it sinusoidally oscillating. Analog tape recordings were made of the cavitation noise, angle of attack, and camera pulse. Figure 1 is a functional block diagram of the data acquisition system.

The cavitation noise was sensed by a flush mounted hydrophone in the top of the water tunnel's closed jet test section 46 inches (117 cm) downstream from the foil's axis. The hydrophone's output was amplified, filtered through a four pole high pass Butterworth filter with 3db signal attenuation at a frequency of 10 kHz, and then recorded at 15 inches per second (38cm/s) to IRIG direct record standards. The hydrophone was uncalibrated, so all noise measurements were relative to an arbitrary level. The angle of attack, or foil angle signal, was obtained by a Kaman displacement sensor activated by the linear deflection in a mechanical linkage connected to the foil. Foil angle calibrations gave an absolute foil angle measurement error of $\pm$ 0.06 degrees. The camera pulse, a signal generated by the photographic instrumentation, was produced each time a photograph was taken. The foil angle signal and camera pulse were recorded using IRIG standard intermediate band frequency modulation techniques. Details of the experimental apparatus and test procedure are described by Shen and Peterson.[1/2]

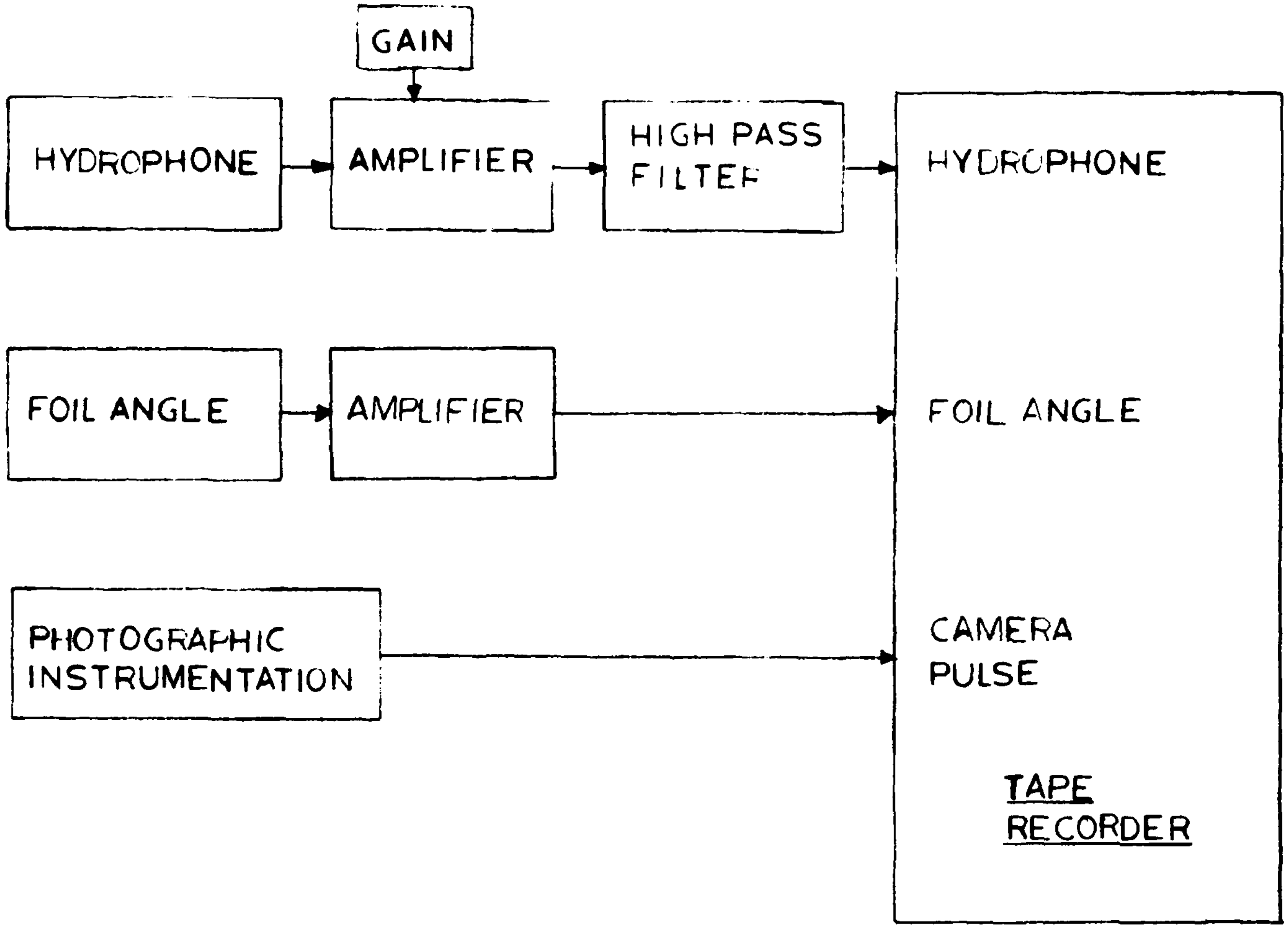


Figure 1 - Data Acquisition Block Diagram

127 data runs were made: 32 static runs where the foil angle was fixed at a given angle of attack, and 95 dynamic runs where the foil was sinusoidally oscillated at various amplitudes and frequencies about a preset positive 3.3 degree attack angle. During these tests, the water speed ranged from 32 to 54 ft/sec (9.7 to 16.3 m/s) and the tunnel pressure ranged from 8.5 to 40 psia (58.6 to 276 kPa). For the static runs, the foil angle ranged from a positive 1 degree angle to positive 4 degrees. For the dynamic runs the foil angle sine wave single amplitude varied from 0.35 to 2.5 degrees; a large portion of the runs were made with a 1 degree oscillation. The oscillation frequencies were 4, 5.5, 7.5, 10, 15, 20 and 25 Hz. The runs were divided into different series; the tunnel pressure and water speed were fixed for each series. For the static runs the series consisted of a range of foil angle settings. Dynamic series had the foil angle sine wave single amplitude held constant and the oscillation frequency was varied.

HYDROPHONE SIGNAL CHARACTERISTICS

The recorded hydrophone signal is a composite of background noise, instrumentation noise, and cavitation noise. Signal processing procedures must differentiate between these noise sources so that only cavitation noise is quantified.

General background noise which contaminates the cavitation noise consists mostly of acoustic emissions from mechanical systems and fluid flow. The character of these emissions changed with run conditions. Instrumentation noise was essentially electrical noise from the tape recorder.

The hydrophone signal was high-pass filtered to reduce the influence of flow noise. Low-pass filtering was used to reduce the influence of the tape recorder noise. During the dynamic runs, the mechanical assembly generated noise. Determining the significance of this noise source relative to cavitation noise required foil oscillation runs under noncavitating conditions as well as identification of the time relationship between the noise components and the angle of attack. Flow noise was generated by turbulence and small gas bubbles as the water flowed past the foil and other boundaries in the test section. Again, tests under noncavitating conditions, showing relationships between noise and angle of attack were required to estimate the influence of this flow noise.

Cavitation noise sensed by the hydrophone consisted of a low-level noise with intense short duration noise bursts of random amplitudes that occurred at random time intervals. During dynamic runs, these short duration bursts were modulated or varied by the foil's changing angle of attack.

The variability of the short duration noise bursts and modulation with angle of attack were the two signal characteristics that prompted the development of an ensemble averaging procedure. For the dynamic runs ensemble averaging produced the average sound pressure variance as a function of time from the start of the foil angle cycle, i.e. a function of foil angle.

DATA REDUCTION

This section gives a detailed description of the signal processing procedures used to reduce the experimental oscillating foil data. First, a general description of these procedures is presented; then the implementation of these procedures is detailed in two parts: Analog Signal Processing and Digital Signal Processing.

GENERAL SIGNAL PROCESSING PROCEDURES

For each experimental run the primary information desired from the hydrophone signal was sound pressure variance (standard deviation squared) over a given frequency interval. This basic measurement took several forms: average sound pressure variance over the entire run, sound pressure variance at each camera pulse occurrence, and sound pressure variance as a function of foil angle. Since the hydrophone was uncalibrated, these measurements were made relative to an arbitrary level.

Since cavitation noise varies in intensity with a time-varying angle of attack, the hydrophone signal from the dynamic runs is a nonstationary random variable. Random variables were treated using the framework given by Bendat and Piersol.[3] Each foil angle cycle was treated as if it was a new run at the same test conditons. Sound pressure variance was obtained from ensemble averages — averages made from the square of hydrophone signal amplitudes measured at the same time or position in each successive foil angle cycle. See Figure 2. For the dynamic runs this procedure produced relative sound pressure variance measurements as a function of foil angle.

The hydrophone signal passed through several processing phases before these relative sound pressure variance measurements were obtained. First, the signal was processed through an analog bandpass filter. The choice of filter settings qualified the sound pressure variance measurements. The next processing phase produced the quasi-stationary relative sound pressure variance (QRSPV). The QRSPV assumed that the hydrophone signal was statistically stationary over a time interval of at least 0.0015 seconds for both static and dynamic runs. An analog multiplier and an averaging filter performed the operation that produced the QRSPV. The averaging filter closely approximated a running-averager;[4] it did not have the long

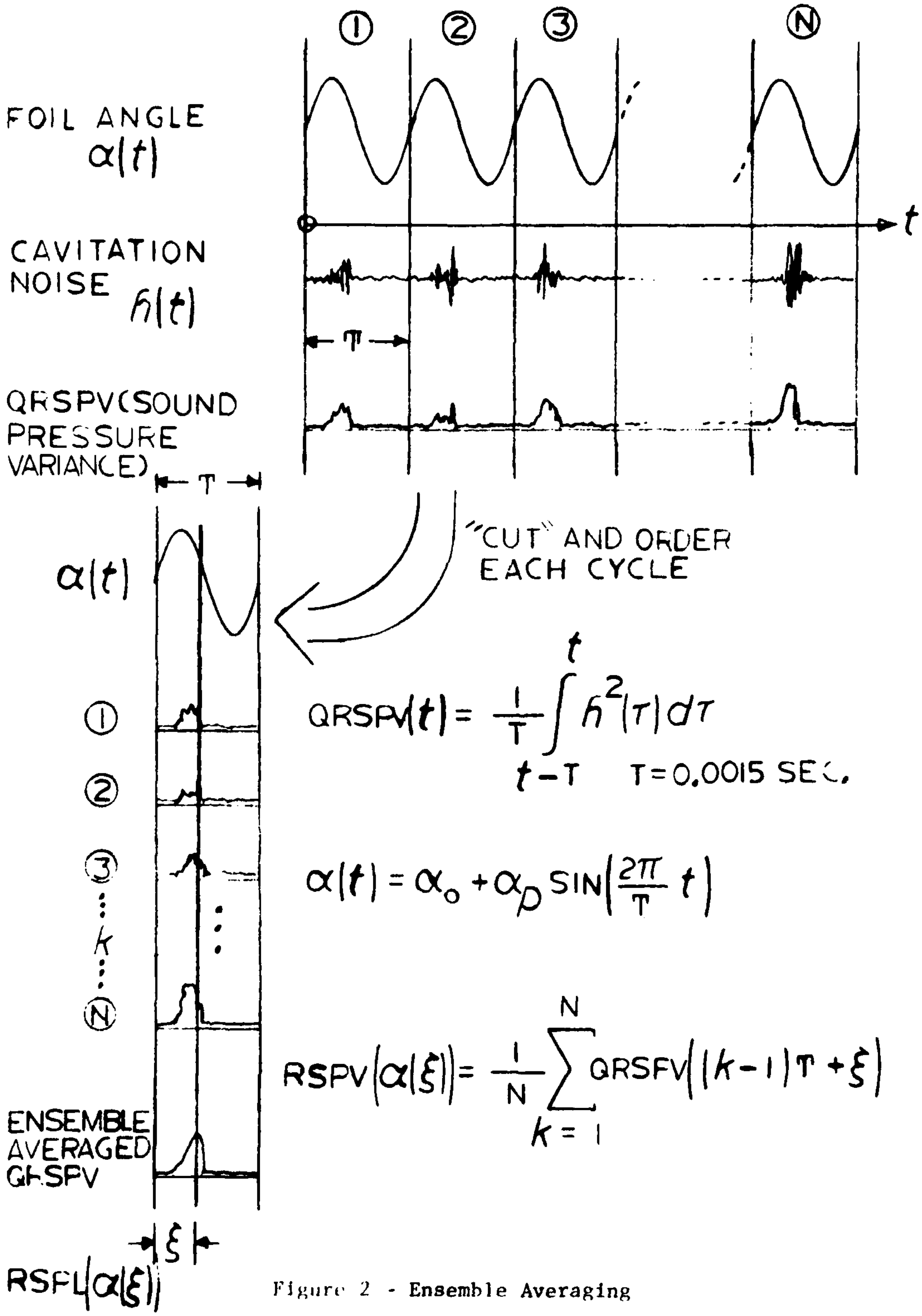


Figure 2 - Ensemble Averaging

"memory" associated with the standard resistor/capacitor (RC) averaging filter. The exact expression for the running-averager that approximated QRSPV as a function of time was:

$$\mathrm{QRSPV}(t) = \frac{1}{T}\int_{t-T}^{t} h^2(\tau)\, d\tau$$

where the integration period T was 0.0015 seconds and $h(t)$ was the filtered hydrophone signal.

All relative sound pressure variance measurements were derived from this QRSPV time history. The average relative sound pressure variance (ARSPV) was the QRSPV averaged over the duration of a nominal 30-second run. The relative sound pressure variance at each camera pulse occurrence (RSPVC) was the QRSPV sampled at each camera pulse. The relative sound pressure variance as a function of foil angle (RSPV) was the QRSPV ensemble-averaged over many foil angle cycles.

Except for the QRSPV at each camera pulse, averaging (either run or ensemble averaging) was performed on the QRSPV to build up statistically reliable results — reduce random error in the relative sound pressure variance measurements. The 0.0015 second averaging period of the QRSPV did not influence the run average; however, this period did limit or bias the detail possible from the ensemble-averaged pressure variance measurements (trade-off with sample rate for the digital processing). In these tests, the greatest foil angle frequency was 25 Hz, so this 0.0015 second averaging period effectively divided the foil angle cycle into about 27 independent intervals.

The QRSPV signal is generally quite random because of the short averaging period. The variability of this signal is represented by the standard deviation of the QRSPV divided by the average QRSPV. This variability was calculated for both run and ensemble averages. Since its value depends on the averaging filter's integration period, its usefulness is restricted.

It does, however, give a feel for the stability of the noise emission at certain foil angles. Also, the QRSPV at a camera pulse could be considered representative of the noise usually occurring at that foil angle if its level is within $\pm$ 1/2 standard deviation about the mean (either run or ensemble averages). From random signal theory[3] the standard deviation to mean ratio (random error) should be inversely proportional to the square root of the run length for gaussian random processes. Since this ratio is near one for many runs, extrapolating from the 0.0015 second averaging period to the 30-second nominal run length gives an expected random error below 5 percent for either run or ensemble-averaged QRSPV measurements. These data are not necessarily gaussian, so the extrapolation procedure was checked for several runs and found reasonable for setting this 5 percent error bound. The check consisted of dividing a run into segments with lengths 1200 times the QRSPV averaging period, or 1.8 second. The QRSPV mean was found for each segment. The standard deviation of these mean values divided by the mean of all these mean values gives the random error estimate for the 1.8 second averaging time. The prescribed random error-to-run length relationship was observed by comparing proportionality constants.

Quantified sound pressure variance levels from statistical run and ensemble averages were produced from a series of operations performed on the recorded hydrophone, foil angle and camera pulse signals. These operations consisted of two different processes: analog signal processing and digital signal processing. The analog procedures produced the QRSPV signal, an amplified foil angle signal that compensated for the

QRSPV's running-average phase shift, a foil angle synchronization pulse that identified each positive going mean level crossing of the foil sinusoid, and a conditioned camera pulse. These data were digitized at a 1600 Hz sample rate and then processed on a digital computer to produce sound pressure variance from the run and ensemble averages as well as the sampled values at each camera pulse. The details of these processing procedures are presented in the remainder of this report.

ANALOG SIGNAL PROCESSING

The analog signal processing procedures produced the quasi-stationary relative sound pressure variance (QRSPV), phase compensated foil angle signal, foil angle synchronization pulse, and conditioned camera pulse. A block diagram of the analog signal processing is given in Figure 3. Intermediate results from analog processing were digitized and further processed on a digital computer to produce the final results.

The recorded data signals were played back at a tape speed of 1-7/8 inches per second (4.8 cm/s), 1/8 their recorded speed. The lower signal frequencies simplified the design of the analog processing circuitry. Except where noted, all references to time and frequency made in this report are "real time" -- as if the data were played back and processed at their recorded speed.

QUASI-STATIONARY RELATIVE SOUND PRESSURE VARIANCE (QRSPV)

The QRSPV time history was the result of the following operations on the recorded hydrophone signal: bandpass filtering, amplification, squaring and running average. The square root of the QRSPV was then taken, to overcome digitizer limitations, and digitized. The status of these operations was monitored by a saturation indicator and a 30-second running average displayed on a digital voltmeter (DVM).

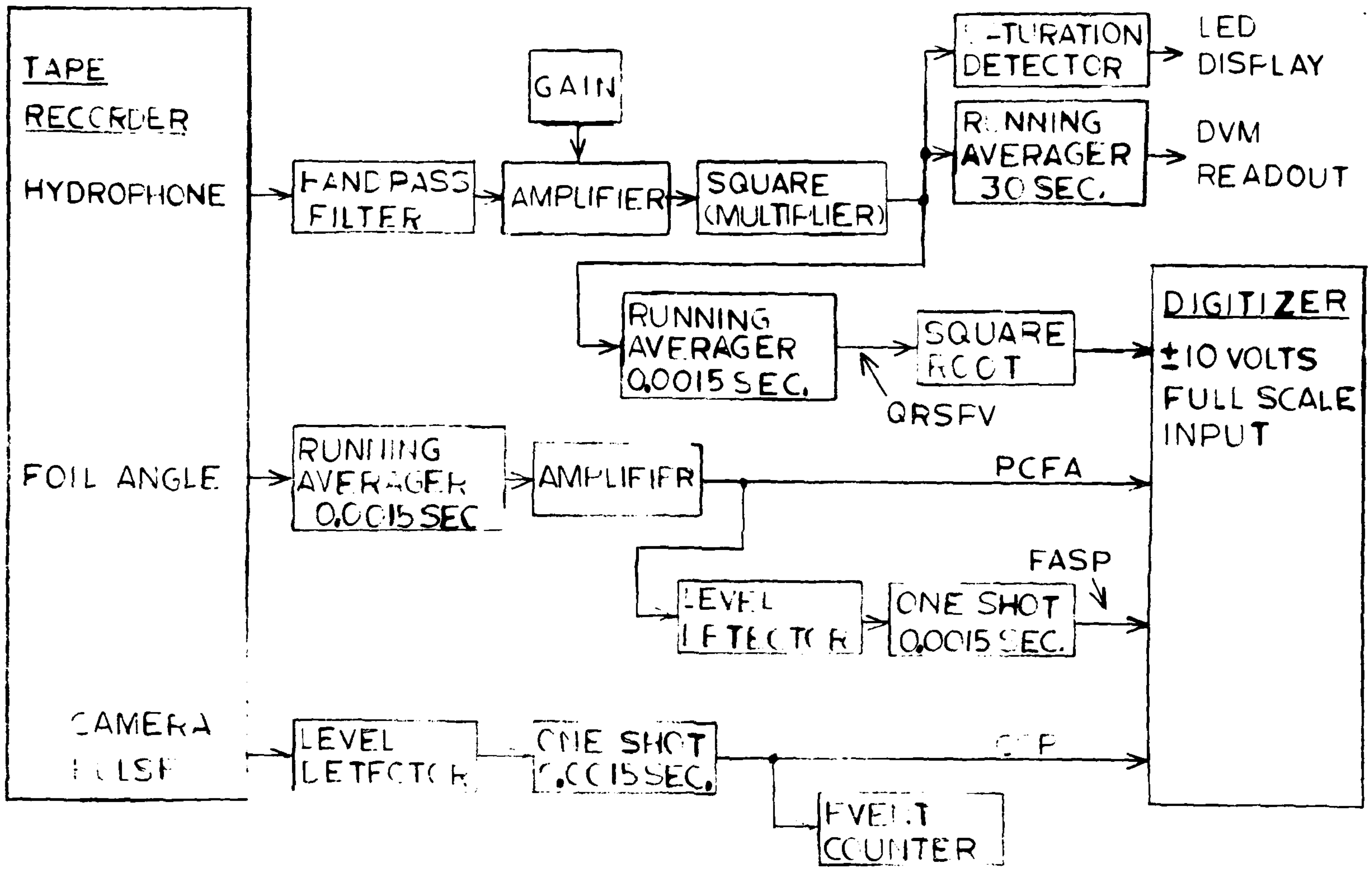


Figure 3 - Analog Signal Processing

Bandpass filtering was the first operation performed on the hydrophone signal; two filter configurations were used. For most runs this signal was filtered by an Ithaco Model 4111 four pole bandpass filter. The high pass filter section had a -3 db attenuation at a frequency of 8 kHz which reduced flow noise in the hydrophone signal. The low pass section had -3 db attenuation at a 40 kHz frequency to reject tape recorder noise. The effective bandwidth of this filter was 30 kHz with a center frequency of 25 kHz.

For selected runs the hydrophone signal was filtered by a General Radio Model 1564-A one-third octave filter. The following center frequencies were used: 10, 12.8, 16, 20, 25.2, 32, and 40 kHz. From reference [5], the American Standard Specification for Octave, Half Octave and Third Octave Band Filter Sets [ANSI S1.11-1966 (R 1975)], the noise bandwidth for these filters is 0.2316 f_m where f_m is the mid-band or center frequency of the third octave filter used. The 10 kHz high pass filter used during data acquisition distorted the results from the 10 kHz center frequency third octave filter. Measurements of this composite transfer function showed that the noise bandwidth was still within ANSI specifications; however, the QRSPV was reduced by a factor of 2.06 and its center frequency was shifted to 10.3 kHz.

After filtering, the hydrophone signal was amplified and then squared. A saturation detector monitored the amplifier's output; overrange conditions (amplifier's output greater than 8 volts) were indicated by a light emitting diode (LED). This indicator was held on for about 0.5 seconds by a timing circuit. The amplifier's gain was selected during playback to prevent overrange conditions. These gains were continuously selectable from 1 to 40.

The amplified signal was then squared using a Teledyne Philbrick Model 4454 analog multiplier. The square root function after the running-average circuit used the same type of multiplier. To obtain the squaring and square root functions, these multipliers were configured as shown in the application section of the Teledyne Philbrick specification sheet titled: 4454/4455 and 4456/4457 Accurate, Fast Multiply-

Divide-Square, Square Root Operators (15M Revised 8/78). The recommended trim resistors and set up procedures were used with these multipliers.

The running-average operators used to obtain the QRSPV (0.0015-second averaging period) and the DVM display (30 second averaging period) give a continuous output that closely approximates the average multiplier signal present during the last averaging period. Signals present before that period have little influence over the output. This averager characteristic tracked the variability in the hydrophone signal. Examples of this performance feature are shown by the response of this circuit to a sine wave burst and to a cavitation noise burst; See Figure 4. This performance was adequate. The choice of averaging period was a tradeoff between statistical variability in the QRSPV and the rate at which the noise intensity changed. The circuit diagram for this averager (used for data at 1/8 recorded tape speed) is given in Figure 5.[4] The step response of this circuit (averager alone) is given in Figure 6. For comparison, this figure also contains the step response of a RC averager. The RC averager (resistor charging a capacitor) would spread the effect of a large noise burst over several time constants since it exponentially forgets past inputs.

The square root of the QRSPV was digitized. Since the digitizer had limited dynamic range (4096 discrete levels cover -10 to 10 volts), the square root operation was necessary to compress the dynamic range of the QRSPV to match the range of the digitizer. The digitized QRSPV -square - root was then squared during the digital processing phase to obtain better small signal detail. A calibration using sinusoidal and random test inputs to the muliplier, running-average and square root circuit combinations produced the QRSPV error curve given in Figure 7. This error curve was used to estimate the error in the final computer results. The average estimated error for 125 runs was 7 percent of the reading for the run averaged QRSPV. The highest estimated error was 22 percent for one of these runs. The ensemble-averaged QRSPV was generally more accurate in the regions of peak noise and less accurate in low noise regions.

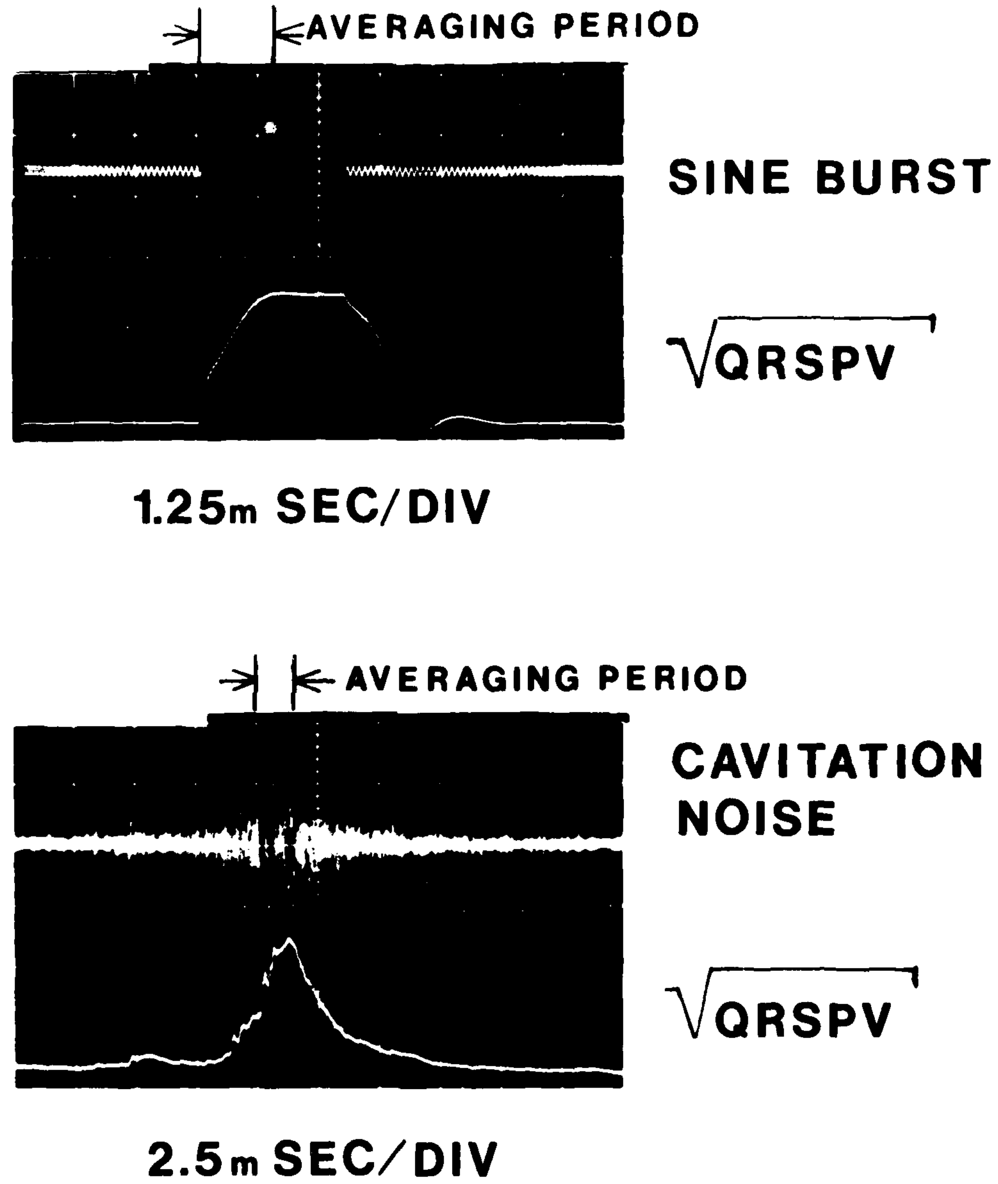


Figure 4 - Running Average Performance

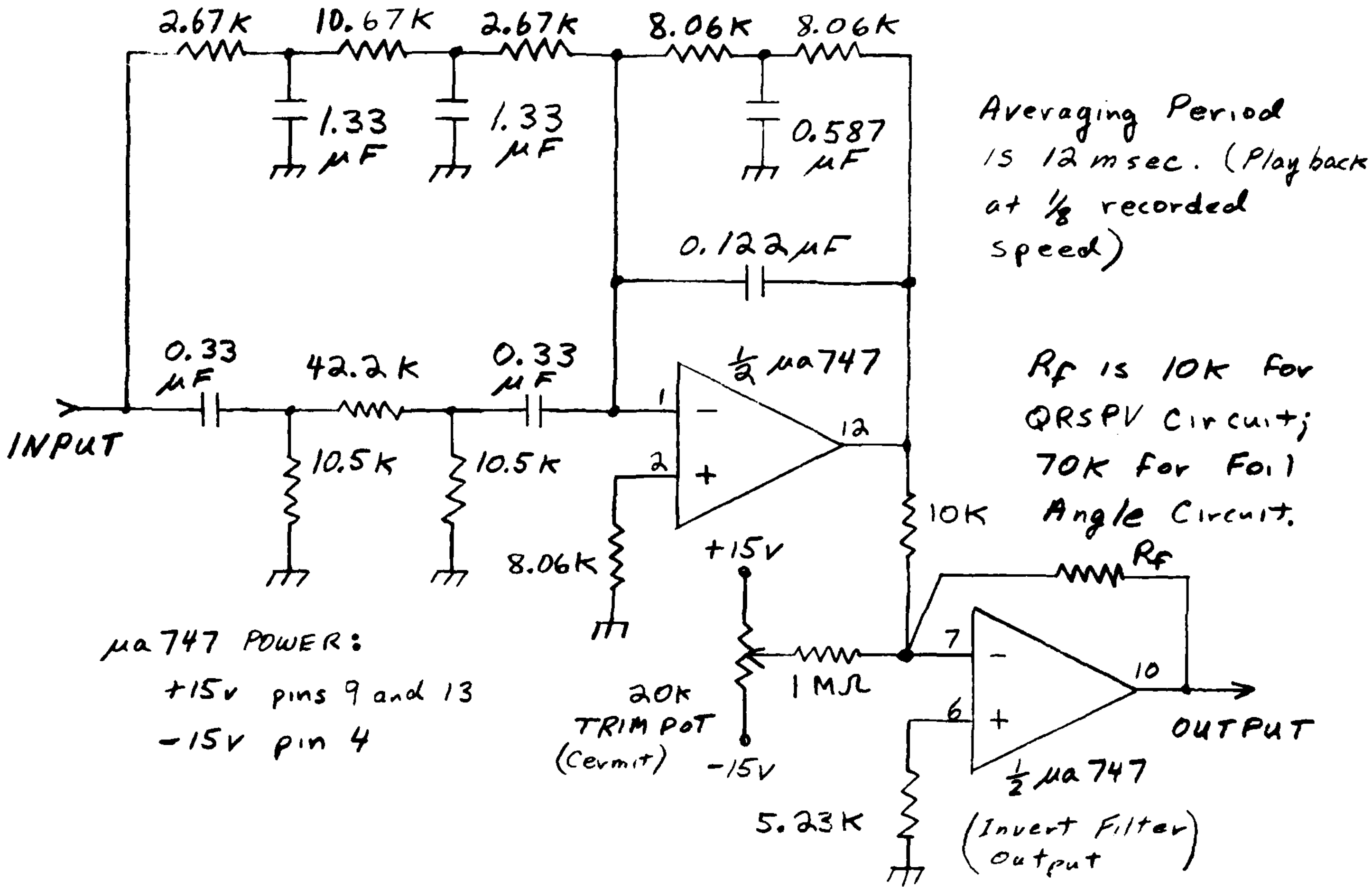


Figure 5 - Running Averager (QRSPV & Foil Angle)

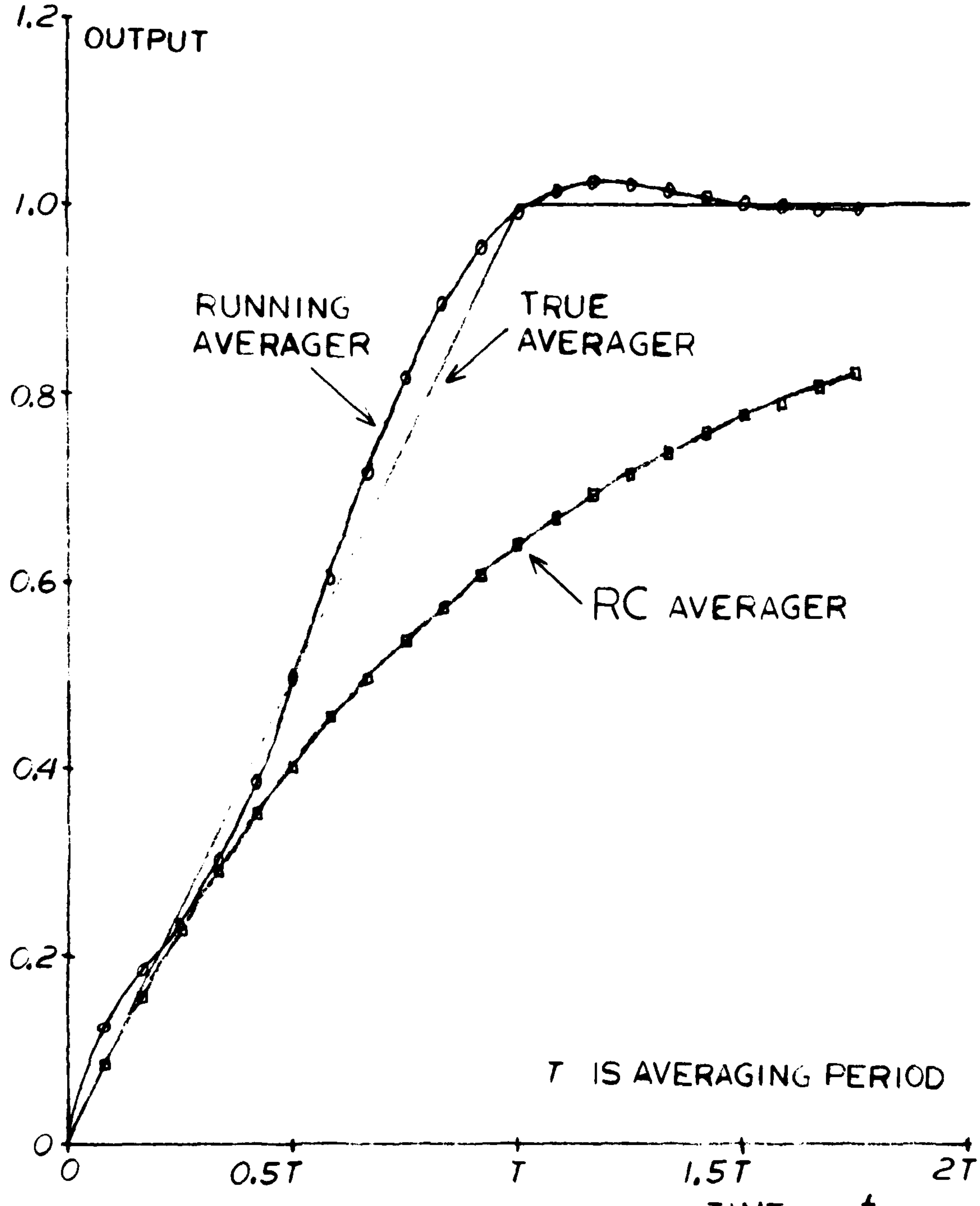


Figure 6 - Response of Running and RC Averager to a Unit Step Input

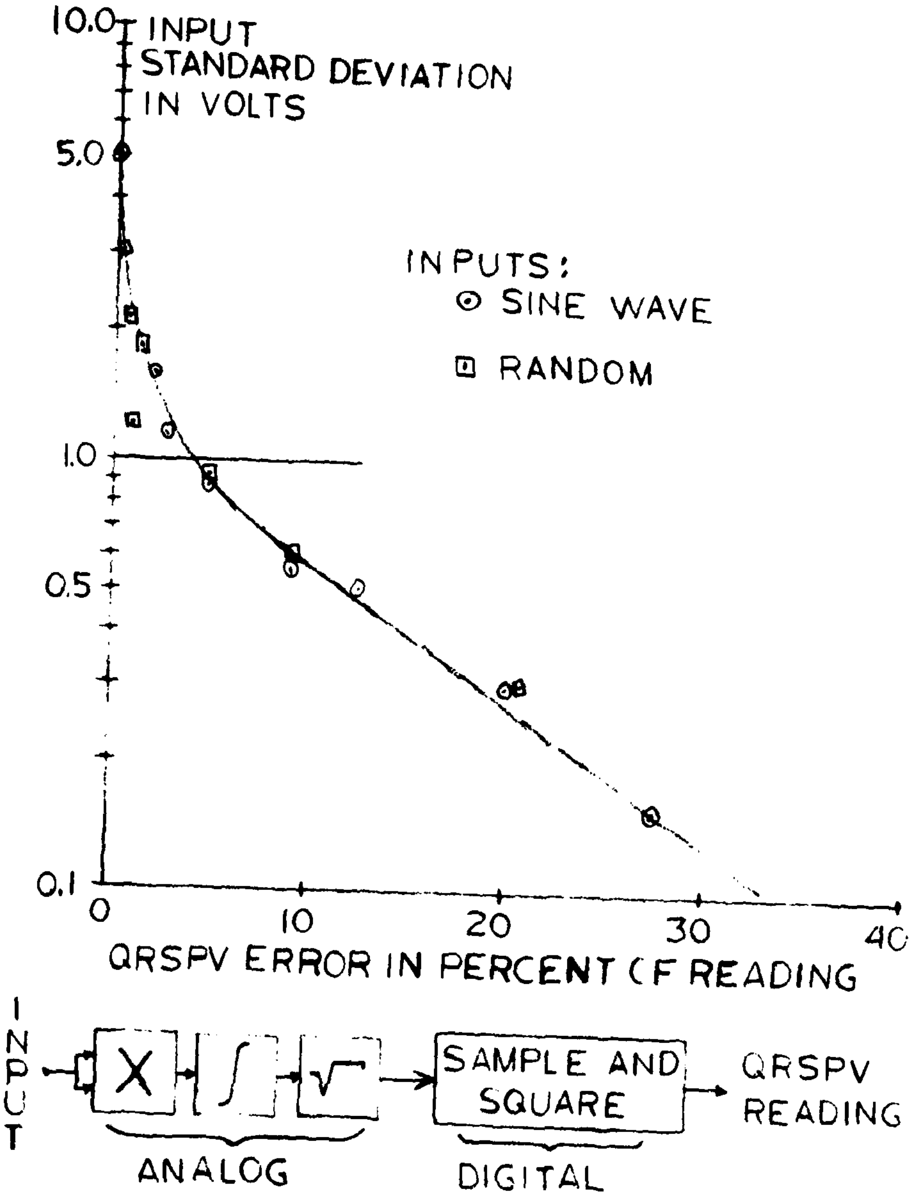


Figure 7 - QRSPV Error

The 30-second average QRSPV displayed on the DVM was recorded and later compared with the run averaged QRSPV on the computer output. These readings gave preliminary results as well as a check on the computer readings. The two readings were close even though they were generally obtained from different sections of test data and with different run times. For 116 runs, the difference between the two readings had a standard deviation of 6.5 percent of reading.

PHASE COMPENSATED FOIL ANGLE (PCFA)

To compensate for phase shifts between QRSPV and foil angle, the foil angle signal was processed through a running average circuit with the same time constant as the unit used for the QRSPV (0.0015 seconds). An amplifier with a gain of 7 brought the $\pm$ 1.414 volt tape recorder full scale signal up to the $\pm$ 10 volt full scale digitizer range. This signal is labeled PCFA on Figure 3.

FOIL ANGLE SYNCHRONIZATION PULSE (FASP)

A foil angle synchronization pulse (labeled FASP on Figure 3) was generated for every positive going mean level crossing of the sinusoidal foil angle signal. This pulse was digitized and used in the computer processing to synchronize the ensemble-averaging procedure.

This 0.0015 second duration pulse was generated by a one-shot triggered by a level detector. The adjustable level detector was driven by the phase compensated foil angle signal. To reduce the influence of tape recorder noise, the level detector had 0.2 volts of hysteresis built in; once the state of the detector changes, the input voltage must swing lower than the preset level by 0.2 volts before the detector reverts back to its original state. The level at which the detector would change states was adjusted manually by using an oscilloscope to estimate the mean of the foil angle. Both QRSPV and foil angle were ensemble-averaged (phase preserved independent of this setting) so this setting was not critical. The duration of the one shot was chosen so that at the 1600 Hz digitizer sample rate, at least two samples of the digitized foil angle synchronization pulse would be at full pulse voltage.

CONDITIONED CAMERA PULSE (CCP)

The camera pulse generated when a photograph was taken was conditioned and digitized. During computer processing, the QRSPV and foil angle were printed whenever one of these pulses was detected.

The circuitry used to condition this pulse was almost identical to the foil angle synchronization pulse circuitry. The range of the detection level was narrowed to improve resolution since the camera pulse from the tape recorder was a damped sinousoid with a 1 to 2 volt peak value. This signal is labeled CCP on Figure 3.

An event counter was used to help locate the camera pulse on tape and to indicate the number of pulses digitized.

DIGITAL SIGNAL PROCESSING

The digital signal processing procedures used the digitized QRSPV-square-root, foil angle synchronization pulse, and camera pulse to calculate the average sound pressure variance over the run, QRSPV and foil angle at each camera pulse, and sound pressure variance as a function of foil angle (ensemble averaged QRSPV). Also calculated were QRSPV standard deviation over the entire run and as a function of foil angle, the number of camera pulses in each run, and the fourier series of the ensemble averaged QRSPV and foil angle.

This computer processing was accomplished in three phases. First, the time histories were digitized using a Hewlett Packard Model 2100S minicomputer and stored on standard computer 1/2 inch magnetic tape. These tapes were then processed on the Center's 6000 series CDC digital computers.

PROCESSING PROGRAM HYPHANS

The computer program HYPHANS processed the magnetic tapes from the HP minicomputer to produce the desired reduced data. These results were then stored on permanent file for use with the format program HYPHFMT.

The results are obtained from one pass of the input tape. During the pass the calibration factors are applied to each data sample. The QRSPV-square-root samples which were originally digitized are squared to obtain QRSPV samples. These QRSPV samples are again squared to produce QRSPV-squared samples. The QRSPV and QRSPV-squared samples, and the number of samples are accumulated for mean and standard deviation estimates over the run. When a camera pulse is detected, its location within the run, the foil angle and QRSPV are stored. For the dynamic runs, ensemble-averaging is performed. When the foil angle synchronization pulse is detected, the averaging index is reset and the foil angle period is accumulated for mean and standard deviation of the foil angle period. As each time step is processed, the foil angle and QRSPV values and their squares are accumulated in arrays where the array element number is the current averaging index. This index is incremented by 1 for every time step that does not contain a foil angle pulse. The index is reset to 1 when a foil angle pulse is detected. Another array is used to accumulate the number of samples accumulated in each array element. A histogram of the foil angle periods is later extracted from this array.

When the tape pass for each run is completed, the accumulated values are processed. The average relative sound pressure variance, ARSPV, over the entire run is given by:

$$\mathrm{ARSPV} = \frac{1}{M}\sum_{\eta=1}^{M} \mathrm{QRSPV}(t_\eta)$$

The QRSPV standard deviation is:

$$\sigma_{QRSPV} = \sqrt{\frac{1}{M}\sum_{\eta=1}^{M} \mathrm{QRSPV}^2(t_\eta) - \mathrm{ARSPV}^2}$$

where M is the number of samples in the run and t_η is the time of each sample in the run. The ensemble averages are formed using the same basic equations at each index into the foil angle cycle. First, however, an improved estimate of the foil angle period is made and the accumulated values are again averaged so that one foil angle cycle will always consist of 64 equal sections or elements regardless of the foil's oscillating frequency.

Tape recorder tape speed variations, noise affecting the foil angle synchronization pulse circuitry, and the sampling process all introduce time base jitter. An occasional noise burst or tape recorder dropout could prematurely reset the averaging index. Conditions could also exist where the index is not reset until the end of the next cycle. The influence of these factors on the final results must be reduced or identified. Ensemble-averaging of the foil angle not only synchronizes it with the ensemble averaged QRSPV and to the time base, but it also provides a check on the ensemble-averaging process. It should produce a sinusoid with a known amplitude and period to compare with previously processed experimental data.[1] The foil angle period histogram also aids in verifying the test results. A refined estimate of the foil angle period is made by taking the original "raw" values for the period's mean and standard deviation (sigma) and then averaging this histogram over the interval from mean minus 4 sigma to mean plus 4 sigma. The raw and refined values are printed in the output to verify the procedure.

These steps were taken to improve the quality of the data; however, little change was noted. Only about five of the runs had their period modified by more than one sample period (reciprocal of sample rate). The final period standard deviation (time base jitter) was generally less than 1 percent of the mean foil angle period. The foil angle amplitudes and frequencies were compared to previously processed results where power spectrum methods were used to estimate these signal parameters. The standard deviation of the difference between the two amplitudes was the equivalent of 0.01 degrees. The standard deviation of the difference between the two frequencies was 0.016 Hz for a frequency range from 4 to 25 Hz.

The ensemble averages are formed by dividing this refined foil angle period into 64 increments and accumulating (interpolating as necessary) the ensemble accumulations over these new increments. Equations similar to those presented earlier for ARSPV and σ_{QRSPV} are then applied to these accumulations at each increment where M is also an accumulated value.

Once these values are obtained, they are printed and stored on permanent file. With this program, the output format is not very descriptive. Another program, HYPHFMT, presents the results in a more useful format.

FORMATTING PROGRAM HYPHFMT

The program HYPHFMT takes the results stored on permanent file by HYPHANS, combines them with a test condition summary file, and reproduces them on output. The Fourier series of ensemble-averaged foil angle and QRSPV is also presented, as are plots of ensemble-averaged QRSPV. The Appendix is a sample output from HYPHFMT. Run number, tunnel conditions (water speed and tunnel pressure), nominal foil angle and amplitude, and the measured foil angle parameters (amplitude, frequency and mean) from previous processing are then combined with the HYPHFMT outputs.

Four pages of computer processed results are obtained for each run. The top of each page contains the test conditions: run number and digital tape file number; tunnel water speed and pressure; nominal foil angle amplitude and frequency; the nondimensional coefficients of Reynolds number, cavitation number and reduced frequency; and the foil angle single amplitude and mean from the earlier data reduction.

In addition, the first page contains the calibration correction factor, sample rate, hydrophone variance or QRSPV averaged over the run, and the camera pulse results. The sample rate presented in the output is the rate used at 1/8 the recorded speed. The hydrophone variance or QRSPV results contain the number of samples in the run, the mean or average QRSPV over the run, the QRSPV standard deviation and the standard deviation-to-mean ratio. The camera pulse results are next: the element or pulse number, the period in samples between camera pulses (the number for the first element is from start of run), the foil angle at that pulse and the hydrophone variance or QRSPV for that pulse.

The second page contains tables of the ensemble-averaged (signal averaging) results. First, the total number of foil angle pulses and the foil angle period and standard deviation are printed from both the "raw" and the refined (adjusted) procedures. The ensemble-averaged table contains: the element from 1 to 64 (foil angle period divided into 64 intervals), the number of samples used to produce the averages, the ensemble-averaged foil angle mean and standard deviation, the hydrophone QRSPV (variance) mean and standard deviation, and the QRSPV standard deviation-to-mean ratio. The other five columns contain the discrete Fourier series results: the harmonic index and the magnitude and phase for ensemble-averaged foil angle and QRSPV.

The discrete Fourier series of the ensemble-averaged foil angle and QRSPV is generated by using Fast Fourier Transform (FFT) procedures. The magnitude and phase terms presented in the output are the terms necessary to reproduce ensemble-averaged foil angle and QRSPV at each sample point. The following equation is used:

$$\alpha_n = a_0 + \sum_{K=1}^{31} a_K \, \mathrm{SIN}\left(\frac{2\pi}{64} K(n-1) + \phi_K\right)$$

where a_K are the magnitude terms and ϕ_K are the phase terms at each harmonic, K. Complete reproducibility is, however, not possible because the 32nd harmonic was not saved during the FFT computations.

The third and fourth output pages contain line printer plots of ensemble-averaged QRSPV and its standard deviation-to-mean ratio. For each of the 64 points these results are scaled by 100 increments; the maximum value generally sets the value of the 100th increment. The scaling interval is printed at the top of the plot. The increment value at each foil angle is printed in the left column. The values for these plots come directly from the tables on the second page.

CONCLUSION

This application of ensemble-averaging principles is a good example of their power in satisfying the data reduction needs for certain classes of variable or nonstationary data. The results produced by these procedures were used by Shen and Peterson to analyze the cavitation noise generated by an oscillating hydrofoil. These quantitative results allowed the correlation of cavitation noise with observed phenomena such as cavitation inception and termination and cavity length. The magnitude and location within the foil angle cycle of the generated noise were important elements in this analysis.

These data reduction procedures produced good results. The run lengths were long enough to keep statistical sampling error (random error) less then 5%. The circuitry used to produce the QRSPV measurement was generally operated at signal voltage levels that resulted in an average error of 7%. And time base jitter was generally less than 1% of the foil angle period. Since the foil angle amplitude and frequency obtained from the ensemble averaging procedure gave values that were nearly identical to earlier results obtained using power spectrum methods, the ensemble averaging procedure was well verified.

Use of these procedures could benefit other experimental programs in which random data is modulated by a cyclic time function. Noise experiments with cavitating propellers is one such example.

Additional improvements could be made. Dedicated hardware and a minicomputer at the test site would allow near real time response. Also, since the analog multipliers introduce most of the error associated with these procedures, improvement is possible with better equipment selection.

REFERENCES

1. Shen, Young T. and Peterson, Frank B., "Unsteady Cavitation on an Oscillating Hydrofoil," 12th Symposium on Naval Hydrodynamics, David Taylor Naval Ship R&D Center, Washington, D.C. (Jun 5-9 1978).

2. Shen, Young T. and Peterson, Frank B., "The Influence of Hydrofoil Oscillation on Boundary Layer Transition and Cavitation Noise," 13th Symposium on Naval Hydrodynamics, Tokyo, Japan (Oct 6-10 1980).

3. Bendat, Julius S. and Piersol, Allan G., "Random Data: Analysis and Measurement Procedures," Wiley-Interscience, New York, New York (1971).

4. "Applications Manual for Operational Amplifiers", Philbrick/ Nexus Research, A Teledyne Company, Dedham, Mass., (1969) page 76.

5. "American National Standard Specification for Octave, Half-Octave, and Third-Octave Band Filter Sets (ANSI S1.11-1966 R1975)," American Standards Association, Inc., New York, New York, 1966 (Reaffirmed 1975).

APPENDIX
SAMPLE OUTPUT FROM HYPHPNT

R U N 1409 F I L E 15

WATER SPEED= 48.51 FT/SEC. NOMINAL FREQ.= 7.5 HZ. NOMINAL AMP.= 1.50 DEG. TUNNEL PRESSURE= 18.50 PSI.

REYNOLDS NUMBER= 3.49E+06 CAVITATION NUMBER= 1.15 REDUCED FREQUENCY= .384 FOIL ANGLE. MEAN= 3.340 AMPLITUDE= 1.556

CALIBRATION CORRECTION FACTOR IS 1.0000E+00

SAMPLE RATE= 200.000

HYDROPHONE VARIANCE RESULTS OVER RUN

SAMPLES= 72011 MEAN= 2.5829E+01 STD.DEV.= 7.6587E+01 STD.DEV./MEAN= 2.9651E+00

CAMERA PULSE RESULTS

NUMBER OF PULSES FOUND= 32

ELEMENT	PERIOD IN SAMPLES	ANGLE IN DEG	HYDROPHONE VARIANCE
1	897	4.335	4.62250
2	2145	4.441	6.25000
3	2142	4.644	6.25000
4	2144	4.876	9.30250
5	2143	4.924	9.92250
6	2143	4.869	34.81000
7	2143	4.773	37.21000
8	2143	4.451	19.80250
9	2143	4.141	113.42250
10	2144	3.771	122.10250
11	2143	3.365	82.81000
12	2143	3.095	110.25000
13	2143	2.725	23.52250
14	2144	2.383	5.52250
15	2142	2.103	9.30250
16	2143	1.897	3.80250
17	2141	1.849	3.42250
18	2144	1.823	4.20250
19	2144	1.884	3.61000
20	2142	2.084	3.42250
21	2144	2.335	3.06250
22	2144	2.654	2.72250
23	2143	3.034	4.20250
24	2143	3.343	2.72250
25	2143	3.668	2.72250
26	2142	4.074	4.62250
27	2142	4.399	6.60250
28	2144	4.679	4.20250
29	2143	4.876	8.70250
30	2144	4.911	20.70250
31	1414	2.216	2.10250
32	729	4.927	13.69000

R U N 1429 F I L E 15

WATER SPEED= 48.51 FT/SEC. NOMINAL FREQ.= 7.5 HZ. NOMINAL AMP.= 1.50 DEG. TUNNEL PRESSURE= 10.50 PSI.

REYNOLDS NUMBER= 3.49E+05 CAVITATION NUMBER= 1.15 REDUCED FREQUENCY= .354 FOIL ANGLE, MEAN= 3.340 AMPLITUDE= 1.556

SIGNAL AVERAGING RESULTS
NUMBER OF FOIL ANGLE PULSES= 338
MEAN OF FOIL ANGLE PERIOD IN SAMPLES= 2.1346E+02 STD.DEV.OF FOIL ANGLE PERIOD IN SAMPLES= 1.1213E+00
NUMBER OF ADJ.FOIL ANGLE PULSES= 337
MEAN OF ADJ.FOIL ANGLE PERIOD IN SAMPLES= 2.1345E+02 STD.DEV.OF ADJ.FOIL ANGLE PERIOD IN SAMPLES= 1.1213E+00

ELM	SAMPLES	ANGLE MEAN	ANG STD DEV	HY VAR MEAN	HVR STD DEV	HVR SDV/MN
1	1127.	3.379	.044	1.367	.436	.222
2	1127.	3.539	.044	2.162	.450	.218
3	1127.	3.640	.051	2.210	.461	.209
4	1127.	3.795	.049	2.437	.579	.238
5	1127.	3.941	.052	2.515	.734	.281
6	1127.	4.[illegible]	.051	3.147	1.086	.357
7	1127.	4.231	.048	3.214	.879	.274
8	1127.	4.359	.047	3.476	1.089	.313
9	1127.	4.479	.043	3.641	1.158	.318
10	1127.	4.593	.040	3.532	1.175	.307
11	1127.	4.697	.038	4.410	1.662	.377
12	1127.	4.766	.034	5.544	2.472	.446
13	1124.	4.832	.029	8.046	4.512	.561
14	1124.	4.884	.027	9.795	4.740	.484
15	1124.	4.92[illegible]	.024	11.724	5.695	.486
16	1124.	4.937	.023	13.743	8.860	.645
17	1124.	4.94[illegible]	.023	14.464	9.643	.667
18	1124.	4.927	.024	14.577	8.751	.600
19	1124.	4.897	.026	16.123	13.945	.865
20	1124.	4.85[illegible]	.029	19.562	15.353	.785
21	1124.	4.797	.031	23.271	19.241	.827
22	1124.	4.733	.034	25.756	21.469	.834
23	1124.	4.619	.039	29.391	30.142	1.036
24	1124.	4.503	.041	37.419	36.564	.977
25	1124.	4.379	.044	49.509	50.739	1.023
26	1124.	4.243	.047	56.961	58.389	1.027
27	1124.	4.109	.048	73.529	106.022	1.440
28	1124.	3.952	.051	86.963	96.448	1.109
29	1124.	3.813	.055	118.239	115.563	.977
30	1124.	3.652	.053	181.363	228.235	1.255
31	1124.	3.508	.053	198.505	201.976	1.017
32	1124.	3.354	.052	189.421	209.849	1.108
33	1124.	3.233	.049	157.394	162.791	1.036
34	1124.	3.131	.056	112.952	140.433	1.243
35	1124.	2.955	.060	52.084	60.597	1.163
36	1124.	2.814	.056	20.958	24.105	1.150
37	1124.	2.679	.058	11.529	7.401	.636
38	1124.	2.547	.059	9.007	4.808	.534
39	1124.	2.424	.055	7.45[illegible]	3.830	.514
40	1124.	2.337	.052	6.456	3.346	.518
41	1124.	2.233	.051	5.278	2.579	.489
42	1124.	2.109	.047	4.406	1.833	.409
43	1124.	2.025	.044	3.729	1.439	.386
44	1124.	1.955	.039	3.316	1.186	.358
45	1124.	1.899	.034	2.984	.997	.334
46	1124.	1.853	.031	2.924	.924	.327
47	1124.	1.823	.029	2.723	.849	.312
48	1124.	1.837	.028	2.512	.767	.294
49	1124.	1.835	.027	2.47[illegible]	.638	.258
50	1124.	1.817	.028	2.339	.610	.261
51	1124.	1.842	.029	2.195	.587	.267
52	1124.	1.883	.030	2.138	.518	.246
53	1124.	1.939	.033	2.027	.498	.246
54	1124.	2.003	.037	1.982	.477	.240
55	1124.	2.091	.040	1.939	.449	.232
56	1124.	2.182	.042	1.954	.414	.224
57	1124.	2.287	.045	1.827	.420	.230
58	1124.	2.402	.049	1.807	.405	.225
59	1124.	2.52[illegible]	.052	1.81[illegible]	.387	.214
60	1124.	2.651	.054	1.825	.409	.224
61	1124.	2.791	.057	1.866	.430	.214
62	1124.	2.933	.061	1.886	.395	.209
63	1124.	3.082	.064	1.918	.408	.213
64	953.	3.215	.052	1.949	.396	.203

HARM	ANGLE MAG	ANGLE PHS	HVRMN MAG	HVRMN PHS
0	3.336	.0	25.850	.0
1	1.557	2.4	42.360	289.1
2	.039	276.6	32.303	121.0
3	.019	174.9	25.368	307.3
4	.002	323.3	20.503	133.4
5	.008	186.3	15.965	319.8
6	.002	86.3	12.086	142.9
7	.004	161.4	9.620	324.5
8	.001	72.7	7.492	150.0
9	.002	170.5	5.285	334.7
10	.001	68.2	3.701	158.4
11	.001	165.5	2.519	349.0
12	.001	60.4	1.437	192.0
13	.001	141.6	.761	64.5
14	.001	40.4	.850	308.1
15	.000	359.5	1.084	158.1
16	.001	20.1	1.119	350.8
17	.000	82.2	1.125	173.4
18	.001	47.4	1.213	357.7
19	.001	107.0	1.210	188.3
20	.001	61.8	1.071	19.6
21	.001	63.0	.926	212.0
22	.001	52.4	.757	51.6
23	.001	43.8	.566	260.7
24	.001	20.7	.412	121.0
25	.001	44.2	.376	344.7
26	.001	38.9	.450	197.2
27	.001	54.2	.536	44.5
28	.001	38.5	.548	245.7
29	.001	51.8	.535	76.7
30	.000	46.7	.530	266.6
31	.000	67.5	.487	91.7

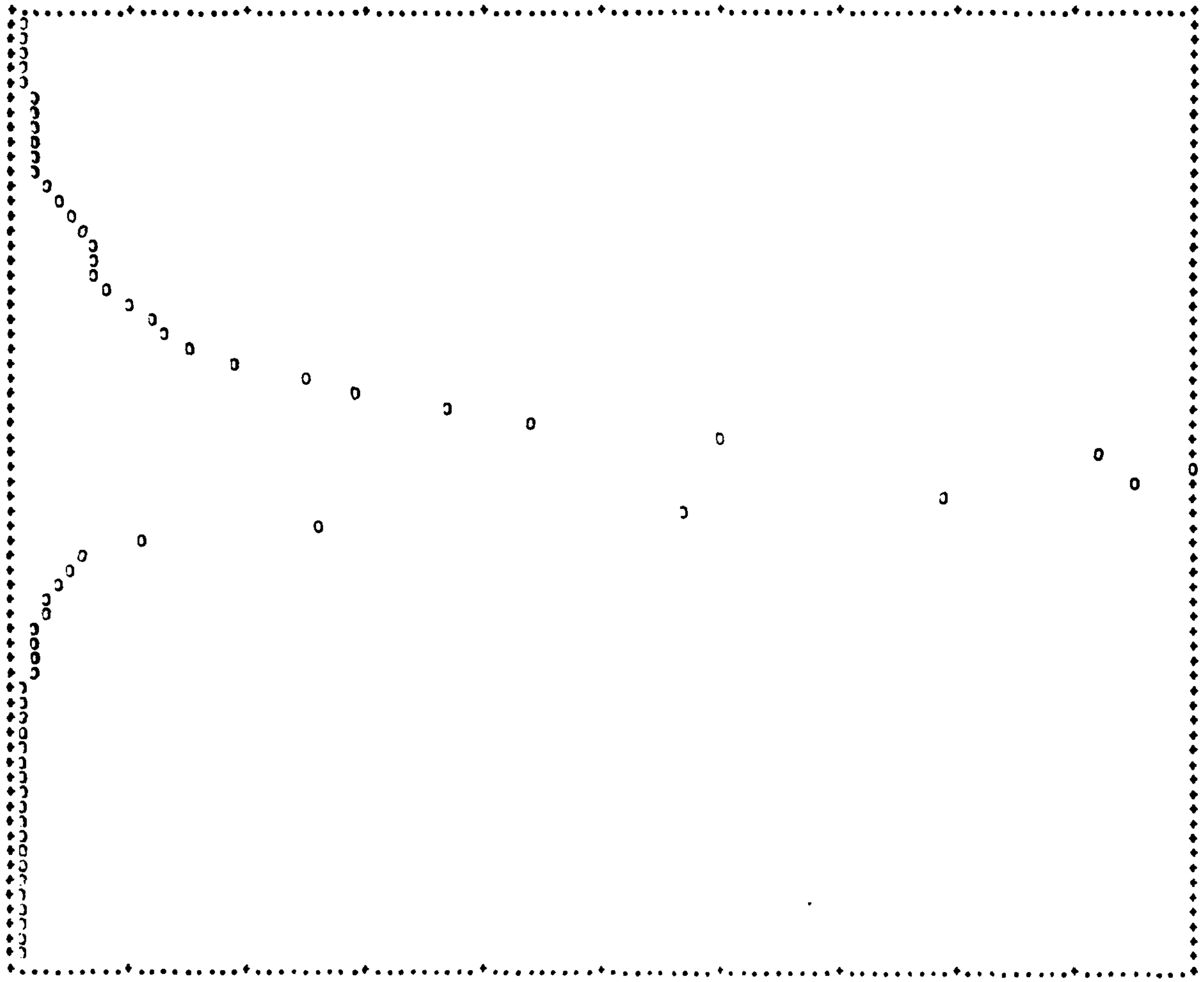
R U N 1419 F I L E 15

WATER SPEED= 48.51 FT/SEC. NOMINAL FREQ.= 7.5 HZ. NOMINAL AMP.= 1.50 DEG. TUNNEL PRESSURE= 19.59 PSI.

REYNOLDS NUMBER= 3.49E+06 CAVITATION NUMBER= 1.15 REDUCED FREQUENCY= .384 FOIL ANGLE. MEAN= 3.348 AMPLITUDE= 1.556

MEAN HYDROPHONE VARIANCE. SCALED FROM ZERO TO 198.53545

SCALE	FOIL ANGLE (DEG)
1	3.379
1	3.509
1	3.640
1	3.795
1	3.945
2	4.089
2	4.231
2	4.359
2	4.479
2	4.593
2	4.687
3	4.765
4	4.832
5	4.884
6	4.920
7	4.937
7	4.945
7	4.927
8	4.897
10	4.853
12	4.787
13	4.703
15	4.608
19	4.501
25	4.379
29	4.249
37	4.129
46	3.962
60	3.813
92	3.662
100	3.508
95	3.364
79	3.233
57	3.101
26	2.955
11	2.814
6	2.679
5	2.547
4	2.424
3	2.307
3	2.203
2	2.109
2	2.026
2	1.955
2	1.898
1	1.853
1	1.823
1	1.807
1	1.805
1	1.817
1	1.842
1	1.883
1	1.938
1	2.009
1	2.091
1	2.182
1	2.287
1	2.402
1	2.522
1	2.651
1	2.791
1	2.933
1	3.182
1	3.215



R U N 1429 F I L E 15

WATER SPEED= 48.51 FT/SEC. NOMINAL FREQ.= 7.5 HZ. NOMINAL AMP.= 1.50 DEG. TUNNEL PRESSURE= 18.50 PSI.

REYNOLDS NUMBER= 3.49E+06 CAVITATION NUMBER= 1.15 REDUCED FREQUENCY= .38. FOIL ANGLE, MEAN= 3.340 AMPLITUDE= 1.556

STD.DEV./MEAN RATIO OF HYDROPHONE VARIANCE. SCALED FROM ZERO TO 2.000

SCALE	FOIL ANGLE (DEG)
11	3.379
11	3.509
10	3.640
12	3.795
14	3.940
18	4.089
14	4.231
16	4.359
16	4.473
15	4.593
19	4.687
22	4.766
28	4.832
24	4.884
24	4.920
32	4.937
33	4.946
38	4.927
43	4.897
39	4.850
41	4.787
45	4.703
52	4.608
49	4.500
51	4.379
51	4.248
72	4.109
55	3.962
49	3.813
63	3.662
51	3.508
55	3.364
52	3.233
62	3.101
56	2.955
58	2.814
32	2.678
27	2.547
26	2.424
26	2.307
24	2.203
20	2.109
19	2.026
18	1.955
17	1.899
16	1.853
16	1.823
15	1.807
13	1.805
13	1.817
13	1.842
12	1.883
12	1.938
12	2.009
12	2.091
11	2.182
11	2.287
11	2.402
11	2.522
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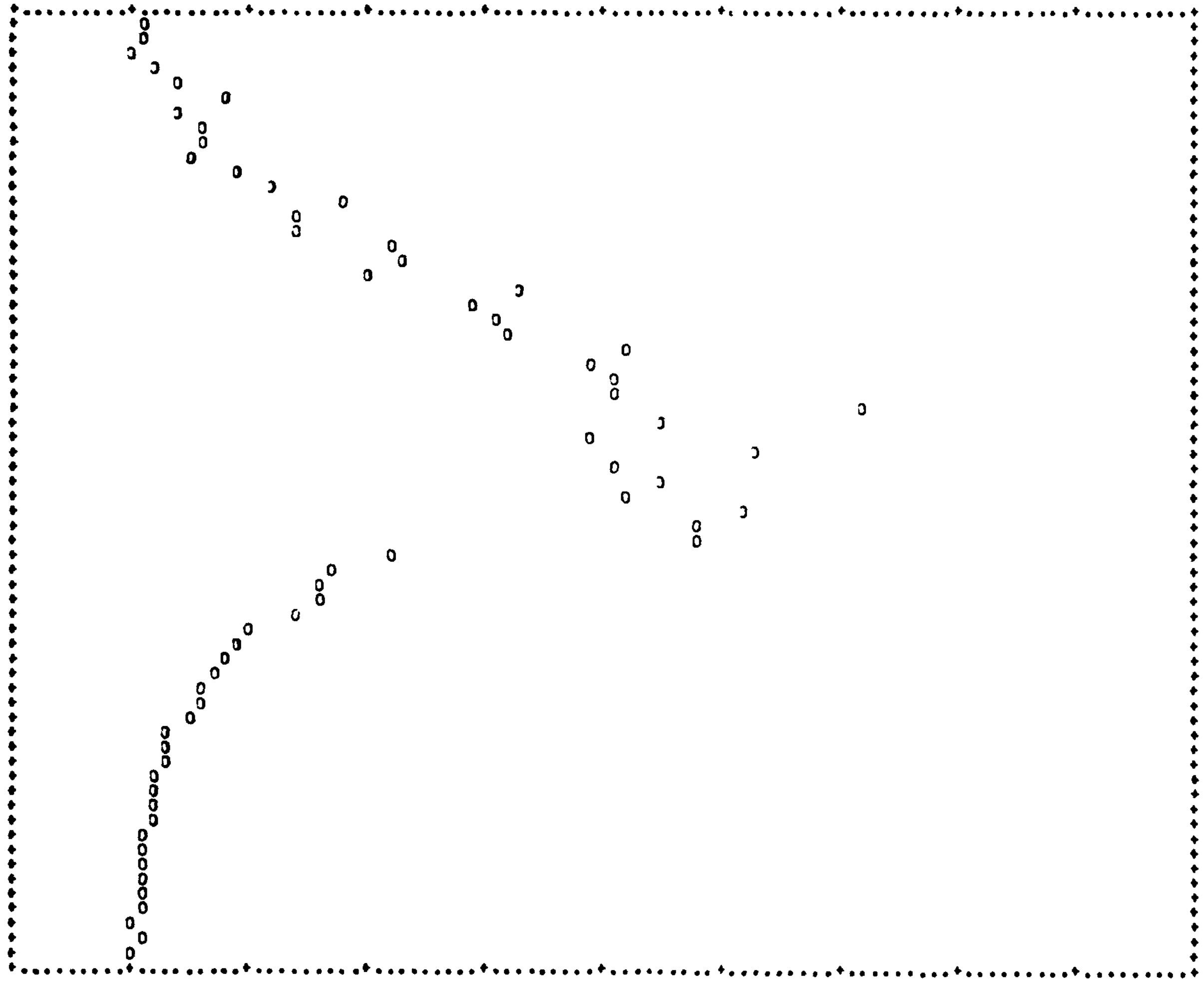
10	2.933
11	3.082
10	3.215



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